It has also been assumed that the electrical properties of the ground may be described by its surface impedance which is a function of the ground constants σ and ε. The integral equation method can be used with any variations of terrain represented as heights along the propagation path. The terrain heights can change abruptly or continuously. The terrain does not need to be described by standard geometrical features or canonical shapes. The terrain can be represented by a completely arbitrary profile. The program assumes that the terrain varies linearly between points input by the terrain file or user. If the program decides that it needs additional terrain points between those given, then linear interpolation is used to determine terrain heights between available terrain heights. The program automatically chooses the spacing so that the terrain is sampled frequently enough for an accurate representation of the terrain variation, and so that the numerical integration of the integral equation is sufficiently accurate, but a compromise is also made so as to prevent excessive computation time. The distance between points should be long so as to minimize computation time, since the computation time is proportional to the square of the number of computation points, but it should be short to accurately represent the terrain and provide an accurate numerical integration.

The analytical details of the integral equation and its derivation are described in the references [33,34]. In both of these references, good agreement is found between this method and other analytical computation methods. Comparisons of calculations with measurements have also been made [6,39,40]. It has been found that for terrain variations smaller than a wavelength, the smooth-Earth and smooth-Earth mixed-path models result in comparable accuracy to the irregular-Earth mixed-path model, so it may be more efficient to use one of the smooth-Earth models.

4. SKY-WAVE PROPAGATION

A medium frequency sky wave will be returned back to Earth by the ionosphere if the degree of ionization in the appropriate regions is sufficient to refract and reflect the incident electromagnetic wave. Ionospheric propagation models for medium frequencies can predict this degree of ionization in the different layers to determine the amount of signal that is refracted and reflected and hence the system performance. The two regions that are responsible for the refraction and reflection of medium frequencies are the D region and the E region. The first region encountered by the sky wave is the D region which extends in a layer that is 50 to 90 km above the Earth's surface [41,42]. It is a region of low electron density whose degree of ionization is determined primarily by solar photoionization. This region usually exists during the daytime. This region has a low electron density and the electrons collide with predominantly neutral gases, so this region absorbs the energy in the MF radio waves that pass through it during the daytime hours [41,42]. The MF sky wave is therefore highly attenuated as it passes through the D layer during the daytime.

At night in the absence of the photoionization created by the sunlight, the ionization in the D region is at a much lower level or is nonexistent, so the D region no longer absorbs the energy from the MF sky wave passing through it. The MF sky wave proceeds to the E region above this D region where it is reflected and refracted. The E-region ionization is from multiple sources that exist all of the time, so it is active during both the daytime and the nighttime. E-region ionization in the daytime is predominantly caused by solar ultraviolet and x-rays, while E-region ionization at night is caused predominantly by cosmic rays and meteors. The E region occurs at heights of 90 to 140 km, and it attains its maximum electron density near 100 km [41,42]. This is the height within the E region that is the predominant reflecting medium for MF propagation at night. Since the sky wave at medium frequencies is strongly attenuated by the electron density in the daytime D region, long distance radio-wave propagation during the daytime is limited by how far the surface wave component of the ground wave can diffract around the Earth and its terrain features. Consequently, ionospheric radio-wave propagation at MF is practical only at night [41,42].

The sky wave can contribute to a desired signal and also generate undesirable interference to the desired signal depending on the distance between the transmitter and receiver. At night the undesirable interference from the sky wave can manifest itself as adjacent and co-channel interference to stations that it would not normally reach in the daytime. System performance for close and far distances between the transmitter and the receiver depend on the frequency and ground conductivity, since the magnitude of the ground wave is a function of these two parameters. The sky wave and the ground wave will add vectorially. At 0.5 MHz over average ground, the ground wave predominates over the sky wave from the transmitter site out to distances of about 150 km, where the two signals are equal. The signals add as vectors, and destructive and constructive interference can occur. At distances beyond 150 km the sky wave is the predominant signal. At a signal frequency of 1.5 MHz, the distance where the two signals are equal reduces to 45 km, because of the increased loss at the higher frequency. At even higher frequencies the attenuation losses of both the ground-wave and the sky-wave signal are greater, so the distance where the signal levels are equal in amplitude becomes smaller. If the transmitter and receiver are close to each other, the ground-wave signal is usually predominant over the sky-wave signal, and the ground-wave signal is normally considered the desired signal. For large separations, the sky-wave signal predominates and is the desired signal. In the region between close and far transmitter to receiver separations, either the sky-wave or ground-wave signal can interfere with the dominant signal and cause possible signal cancellation. The desired signal in many practical cases is the ground-wave signal.

The sky wave at AM broadcast frequencies can actually become stronger with increasing distance from the transmitter, because the sky wave that reaches the receiver represents energy radiated from increasingly lower elevation angles, and the characteristics of MF broadcast antennas in the elevation plane are such that the gain that launches or receives the sky wave increases in magnitude over the lower elevation angles as it passes through and goes beyond the main beam. Beyond this point the gain that launches the sky wave decreases as shown in Figure 4. Figure 4 is an elevation pattern for a quarter-wave monopole antenna that is typically used at a transmitter site.

The MF sky-wave model [7] predicts sky-wave propagation parameters using empirical formulas derived from measured data and assumes an undisturbed ionosphere. The propagation of the sky wave is latitude (actually geomagnetic latitude) dependent, but not all models include this effect. The field strength decreases with increasing latitude [47]. The amount of the decrease is proportional to the path length along which propagation takes place. The field strength can decrease as much as 10 dB with a 10 degree increase in latitude at large distances on the order of 4000 km

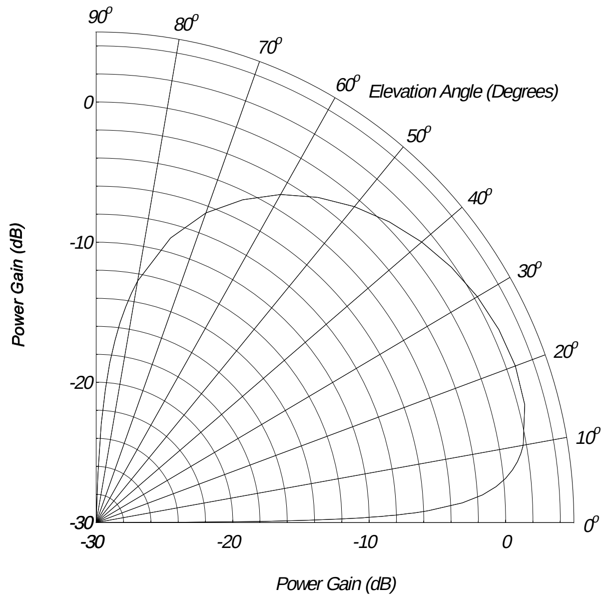

Figure 4. Elevation plane pattern for a quarter-wave monopole on a ground screen.

[43,47]. At 1000 km the decrease in field strength for a 10 degree increase in latitude is only 5 dB. Curves are available for field strengths at other distances and latitudes [47]. The sky-wave models that have latitude and path length dependence can predict the amount of decrease [43]. During fading the field strength amplitude follows a Rayleigh distribution [44] for latitudes less than 40 degrees. The propagation of the sky wave at MF is also dependent on distance, time of day, and frequency. The effects due to frequency are minor.

Semi-empirical algorithms have been produced for ionospheric radio-wave propagation. One such algorithm is that developed by the International Telecommunications Union (ITU) [43,46]. The ITU method is the only one that accounts for the variation of sky-wave propagation with frequency, but it has a frequency-dependent term that reduces the predicted field strength with increasing frequency. One reference, [47], notes that measurements in the United States show a frequency dependence that is exactly the opposite of what the ITU method predicts. The measurements show that signals measured at 1530 kHz at sunset or sunrise are about 15 dB greater than those at 700 kHz. This difference becomes smaller and smaller as the time of day approaches midnight and reduces to 3 to 5 dB at two hours after sunset or two hours before sunrise. The difference at midnight is negligible. Rather than adding the error that is incurred when using the ITU model [47], the effects of frequency for the sky wave are generally neglected. The frequency dependence over the range of 500 kHz to 1600 kHz is small, so it is often ignored and the field strength at 1000 kHz is taken as representative of the entire band [44].

Seasonal dependence has been demonstrated by measurements. The field strength received from a transmitter is at a minimum during the summer and reaches a maximum during spring and fall. The field strength decreases in the winter, but is not as low as the minimum achieved during the summer. The difference between the summer minimum and the spring/fall maximums is about 15 dB at 500 kHz and reduces to about 3 dB at 1700 kHz [44].

There are a number of sky-wave field-strength prediction methods in use. Three methods have been accepted for use in sky-wave propagation prediction: (1) the FCC/Region 2 method for computing sky-wave field strengths [45], (2) the ITU-R (formerly CCIR) recommended method [43,46], and (3) a procedure proposed by Wang [47] for use in the United States and Region 2. All of the procedures assume a reference field strength at 1 km from the transmitter in the development of their field strength curves (FCC Region 2 method) or field strength algorithms (ITU and Wang methods). Using the distance along the path plus other parameters that may be needed, such as frequency and geomagnetic latitude, the annual median field strength can be predicted. Some of the models do not use all of the parameters. This power is modified by the model using the actual transmitter power. The actual antenna gain in the elevation plane for the particular take-off angle needed to reach the reception area is factored in by the model. The take-off angles are also computed by the model using the geometry between the transmitter and receiver site. These methods are each described in more detail in the paragraphs that follow.

The FCC/Region 2 model is actually a combination of the FCC's curve of field strength versus distance for 50 percent of the time (for a year) for distances up to 4250 km, and the Region 2 expression for distances greater than 4250 km [7]. Measurements performed in 1935 were used by the FCC to generate the curve of field strength versus distance. The assumptions made during the development of this curve were that there is no dependency on frequency or latitude for the United States. The FCC considers this curve accurate for all frequencies and latitudes in the United States, but there is latitude dependence outside of the United States. The curve for field strength exceeded for 50 percent of the year is shown in Figure 5. From additional measurements performed from 1939 to 1944, the FCC determined that there is a dependence on latitude [7,48]. The new curves from those measurements can be used for interference analyses. The field strengths are further modified for each analysis by adjusting transmitter power and antenna gain. Because the curve only goes out to about 4250 km, the Region 2 algorithm is used beyond that distance [45]. The Region 2 algorithm is given by [45]:

$$F_c = \frac{231}{3 + \frac{d}{1000}} - 35.5 \tag{49}$$

where F_c is the characteristic field strength in dBuV/m, and d is the distance in km. This expression is adapted from the results of long-distance measurements made in the late 1930s across the Atlantic and from North to South America. They are referred to as the ITU Cairo curves [47]. The field strength that is exceeded 10 percent (upper decile value) of the time is found by adding 8 dB to the

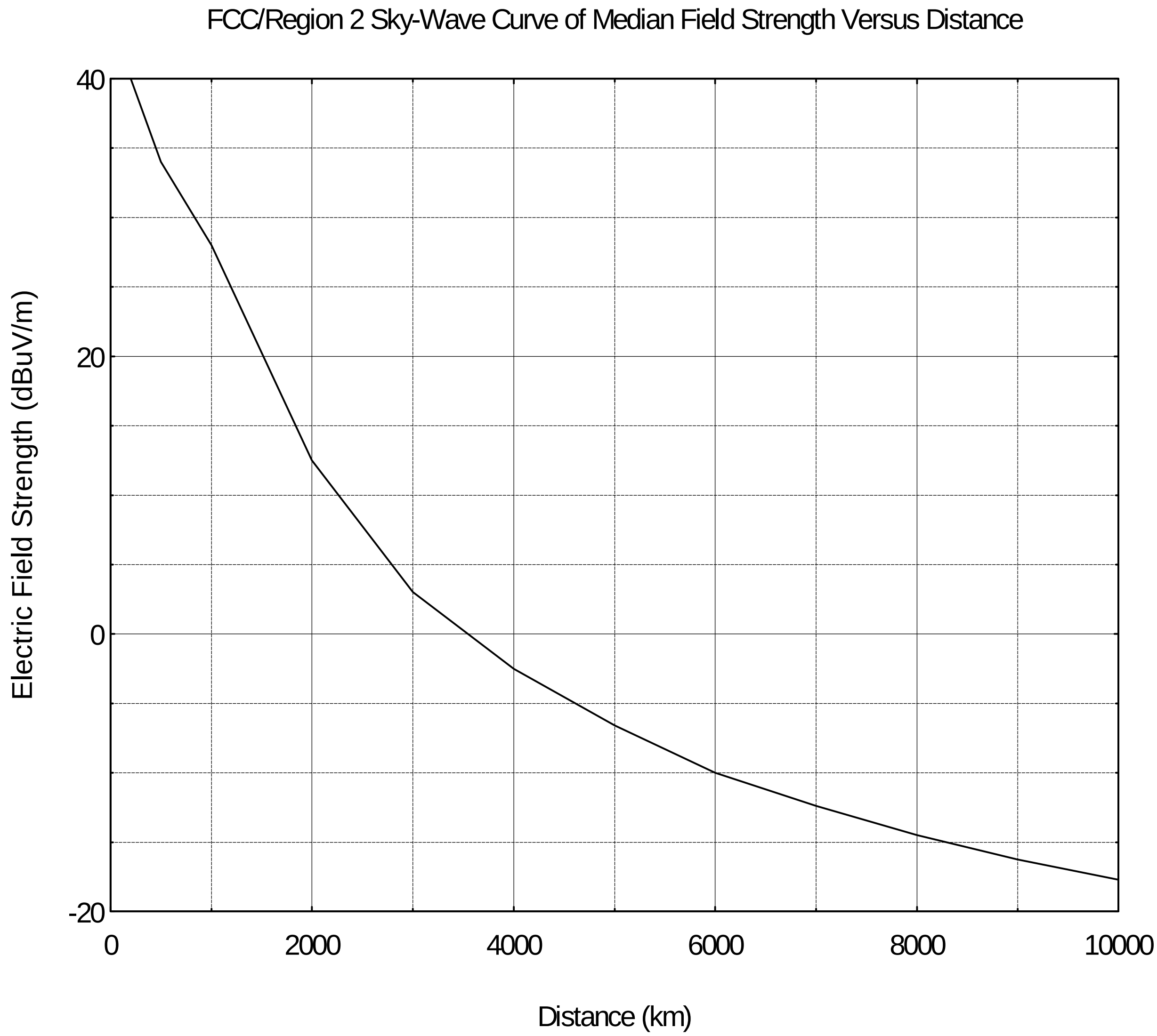

Figure 5. FCC/Region 2 sky-wave curve of median field strength versus distance.

median value of field strength versus distance [47]. The entire curve of field strength exceeded for 50 percent of the time versus distance for the combined FCC and Region 2 methods is shown in Figure 5.

The development of the ITU sky-wave field strength prediction method is a result of many modifications made since the 1930s [47,48]. These modifications were a result of knowledge gained from the measurements. The current ITU method uses the USSR method with certain modifications (such as the United Kingdom sea-gain correction) [7,48]. The expression [7,43] for field strength of the sky wave is:

$$F = V + G_s - L_p + 106.6 - 2\sin(\phi) - 20\log(p_s) - 0.001(K_r)(p_s) - L_t \qquad (50)$$

where F is the field strength in dBuV/m, V is the transmitter cymomotive force above the reference 300 V in dB, G_s is the sea-gain correction in dB, L_p is the excess polarization-coupling loss in dB (defined graphically in ITU Recommendation 435-7 [43]), ϕ is the average of the transmitter and receiver geomagnetic latitudes, p_s is the slant-propagation distance in km, L_t is the hourly loss factor in dB, and K_r is the loss factor in dB including ionospheric absorption, frequency, focusing and terminal losses, and losses between hops.

$$K_r = K + 0.01 b_{sa} R \qquad (51)$$

where R is the twelve-month smoothed international relative sunspot number, b_{sa} is the solar activity factor (b_{sa}=0 for LF band; b_{sa}=4 for MF band for North American paths, 1 for Europe and Australia, and 0 elsewhere). For paths where the terminals are in different regions use the average value of b_{sa} (ITU Recommendation 435-7) [43].

$$K = 3.2 + 0.19 f^{\,0.4} \tan^2[\phi + 3] \qquad (52)$$

where f is the frequency in kHz, and ϕ is the average geomagnetic latitude defined previously. For ϕ > 60 degrees evaluate expression at ϕ = 60 degrees. For ϕ < -60 degrees evaluate expression at ϕ = -60 degrees. For paths shorter than 3,000 km, $\phi = 0.5(\phi_T + \phi_R)$ where ϕ_T and ϕ_R are the latitudes at the transmitter and receiver respectively. The value of L_t is nearly 0 dB for the time period from 4 hours after sunset to 2 hours before sunrise, so this term is ignored for nighttime propagation predictions.

During the daytime, 30 dB is subtracted from the nighttime field-strength prediction or added to the sky-wave loss prediction for the value of L_t(dB). A transition period occurs immediately after sunset and lasts till approximately four hours after sunset, and another occurs during the period from 2 hours before sunrise until sunrise where the field strength goes through this 30 dB change with a very steep slope. The shapes of the curves are not symmetrical for the transition from day-to-night and night-to-day [49].

The D layer of the ionosphere is characterized as having a strong dependence on frequency, but this is present only during the daytime. The E layer is the dominant contributor to LF and MF propagation at night and is only mildly dependent on frequency, so the effects of frequency of this layer can be neglected for most practical purposes [49].

For long distance paths (1000 to 6000 km), when the path is over sea or at least one end of the link is located on or near the seacoast, the phenomenon of sea gain can add from 3 to 10 dB to the predicted field strength [7,43]. However, a knowledge of the land-sea boundary information is necessary to assess the sea-gain phenomena. The sea-gain correction is normally set to 0 dB without this knowledge.

The ITU method makes predictions that depend on both frequency and geomagnetic latitude. The field strength values are not symmetrical about the geomagnetic latitude equal to 0 degrees. A family of field strength curves for 1000 kHz is shown in Figure 6. The ITU notes that this field strength expression predicts lower field strength values as the frequency is increased in the MF band [43], but measurements performed in the United States show that the field strengths are higher at the higher frequencies in the MF band when compared to those measurements at the lower frequencies. Because of this discrepancy, the ITU method has not found wide acceptance as a worldwide prediction method. Davies [43] also refers to measurements and gives an equation that is a function of frequency. He recommends the use of predictions at 1000 kHz to represent the entire MF band.

In an effort to create a valid model that would give reasonably accurate predictions in Region 2, Wang [47] developed an MF sky-wave model after examining all of the available MF methods. The original FCC curves have a hump at roughly 100 km which Wang concluded was due to ground-wave interference present in the 1935 data. The curves become smoother and better behaved after removal of these data points. The Wang expression for field strength is:

$$F_c = 95 - 20\log(d) - [\,6.28 + 4.95\tan^2(\phi_m)]\sqrt{\frac{d}{1000}} \tag{53}$$

where F_c is the characteristic field strength in dBuV/m referenced to 100 mV/m at 1 km, d is the distance in km, ϕ_m = geomagnetic latitude of the midpoint of the path in degrees.

Wang recommends that if d is less than 250 km, then the expression should be evaluated at 250 km. There are also limits that the latitude, ϕ_m, be less than or equal to +60 degrees, and greater than -60 degrees. When compared to the ITU expression, Wang's expression is symmetrical about zero degrees latitude and is not dependent on frequency. Figure 7 shows a family of field strength curves for several values of ϕ_m.

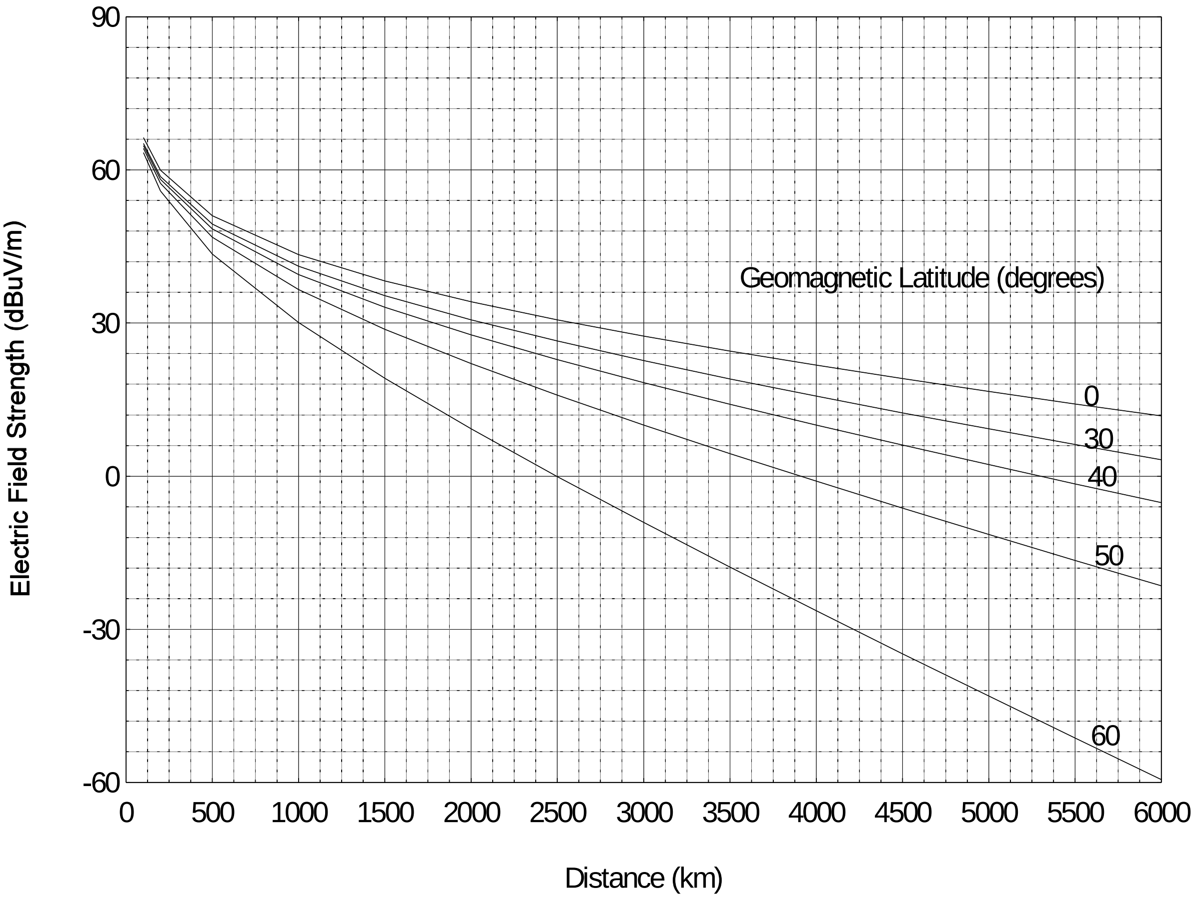

Figure 6. ITU sky-wave curves of median field strength for several values of geomagnetic latitude at 1000 kHz.

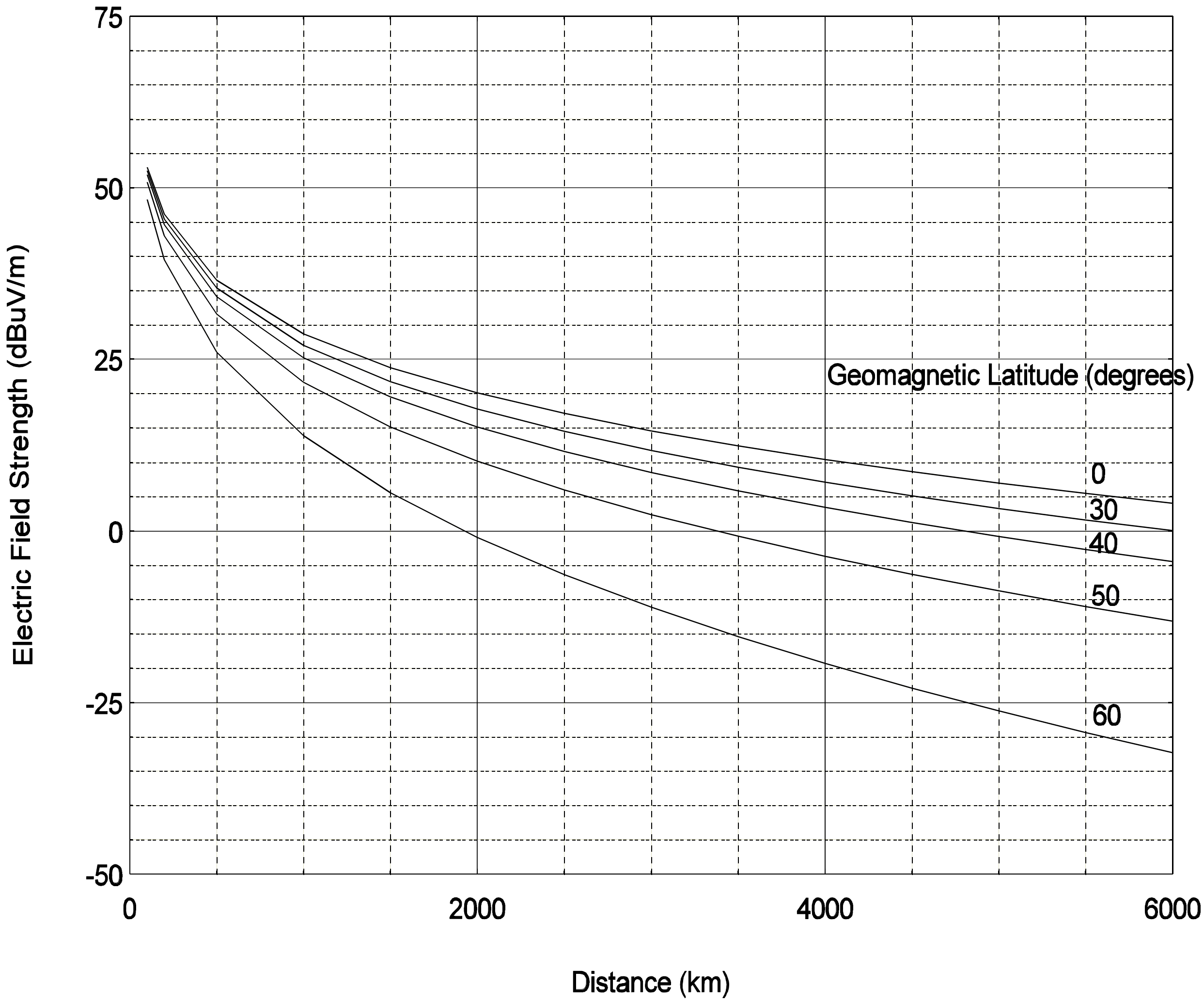

Figure 7. Wang sky-wave curves of median field strength for several values of geomagnetic latitude.